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ABSTRACT

A number of recent policies have tried to improve science learning by increasing the number of science courses required for high school graduation or admission to higher education institutions. But it is highly unlikely that these mandates alone will materially affect the amount and quality of science education for students. Any effort to improve the outcome of science education must carefully consider the effectiveness of the science curriculum. This paper examines options for improving the science curriculum based on research, best extant practices and experience in other countries. Although the word "curriculum" has acquired many different meanings, both in the professional literature and in lay usage, this paper defines curriculum as the intended substantive and pedagogic content of science education to be presented to students in order to develop their knowledge and skills. Alternatives for productivity enhancement are grouped as follows: (1) time; (2) topic and course sequence; (3) curriculum content; and (4) instructional strategies. A summary and discussion are provided. A list of 88 references is included. (CW)

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Increasing Educational Productivity Through Improving the Science Curriculum

Senta A. Raizen

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SUMMARY

A number of recent policies have tried to improve science learning by increasing the number of science courses required for high school graduation or admission to higher education institutions. But it is highly unlikely that these mandates alone will materially affect the amount and quality of science education for students. Any effort to improve the outcome of science education must carefully consider the effectiveness of the science curriculum. This paper examines options for improving the science curriculum based on research, best extant practices and experience in other countries. Although the word "curriculum" has acquired many different meanings, both in the professional literature and in lay usage, this paper defines curriculum as the intended substantive and pedagogic content of science education to be presented to students in order to develop their knowledge and skills.

Goals and Substantive Content of the Curriculum

Policies aimed at improving science education must first define clear goals for that education. Simply stated, who will be taught what? Should there be different goals--and therefore different curricula-- for students of different interests and competencies? Which is of higher priority: the development of scientific talent and technical manpower, or achieving a basic level of scientific literacy for all students? Philosophical differences about what subject matter is most important must be also be resolved. Should teaching of fundamental processes and concepts of say, biology, take precedence over an understanding of one's own body, good health practices, and preparation for sexually responsible conduct leading to good parent behavior? What is the place of technology education in the curriculum?

These goal conflicts cannot simply be papered over. Scientists, together with teachers from the relevant grade levels, science educators, employers, and others with interest and understanding of current needs in science education must define its goals and the core knowledge and understanding to be expected of all students.

Improvements made in curriculum and instruction must be reflected in the ways that student knowledge and performance in science are assessed, and assessments must plumb all important curricular goals.

Increasing Curriculum Effectiveness

Several possible methods of making the science curriculum more efficient are:

-Introducing coherent substantive curriculum content into elementary school to provide a sound foundation for secondary school science;

-providing sufficient challenge and opportunities for student involvement in

science learning at the lower levels to maintain interest (and increase student enrollment) at the secondary level; and

-reforming the secondary school curriculum so that courses, no matter whether aimed at the science-able or designed for general scientific literacy, deal with a limited number of core topics in depth rather than presenting a smattering of many topics as at present.

A move in this directions would be the development of curriculum frameworks such as those suggested by the Indicator Committee of the National Research Council. Frameworks should cover substantial blocks of the curriculum, for example: grades K-5 science, grades 6-8 science, grades 9-12 science, and grades 9-12 science for college-bound students. The frameworks would serve to inform state and local agencies as to the desirable content of textbooks, tests, and their own curriculum guidelines. Specification of curriculum content should be done by scientists, learning researchers and educators. Curriculum content and science learning achieved in other countries can provide a model for what is possible, if not necessarily desirable for wholesale adoption in this country.

If the suggestions above were to be implemented successfully, two improvements could be expected to result:

1. At equivalent stages of their mandated education students would know more science than they do now; and

2. students would further increase their science knowledge and achievement by opting to enroll in additional science courses beyond those required.

In addition to content, several interrelated elements of the curriculum that can be altered to achieve improvement include:

Time. Almost 20 percent of the in-class time in U.S. elementary schools is spent in such non-instructional activities as class business and transition between activities. Furthermore, teachers vary in their ability to keep students engaged in learning from about 80 percent of instructional time to about 60 percent. In order to use time more effectively as an element of the curriculum, greater commitment to the primary purpose of educating students must be demonstrated by the school and the teacher; and time in the classroom needs to be used more efficiently through improved curricula. Additionally, the time spent on science education could be expanded through melding out-of-school science activities with formal classroom instruction and homework.

Sequencing. The science curriculum in elementary school should consist of a coherent sequence of core topics that initially build on the students' experiences and environment and advance to increasingly descriptive knowledge and abstract concepts as students mature. Instead of the stand-alone science courses currently offered in high schools, there should be a parallel progression of courses in the life and physical sciences building on the previous years' learning as is the case in schools in most other countries.

Science instruction in Japan, where students do much better in science achievement than they do in this country, provides an example of the spiral

curriculum advocated by science educators as optimal for science learning.

Beginning with first grade, students spend about ten percent of their time learning science. The science topics taught are grouped into three areas: living things, matter and energy, and the earth and the universe. These topics do not all receive equal emphasis; several are taken up throughout the grades, whereas others are treated only once. The topics are pursued in greater detail and with increasing academic rigor and abstraction in grades 7-9. By upper secondary school, courses parallel the science disciplines (physics, chemistry, biology, earth science). Such an organization allows exploration of core scientific concepts in depth, provided that needless and unproductive repetition is minimized. The spiral curriculum also offers re-enforcement for learning science skills, as students progress to increasingly complex laboratory investigations and research.

Instructional Strategies. Science instruction should take advantage of leads being provided by current research on science learning, science teaching and teacher education. Depth of treatment of the core material needs to be built into the curriculum from elementary school on, even at the expense of having to omit favorite topics. Hands-on experiences in elementary school and laboratory investigations in secondary school should be an integral part of science instruction.

Computer and associated telecommunication technologies offer opportunities for restructuring science education and their potential to enable all students to become scientifically literate should be explored. For example, computers can be used for simulations and exercises not easily performed in school labs.

Investing for the Future

The only evidence that the science curriculum can be made more efficient is provided by the experience of other countries and by a select number of high schools that, year after year, have produced high achievers in science. Neither of these provides convincing evidence for what can be done for the great majority of students in this country. Experimentation must take place to establish whether the suggested reforms actually increase student learning and enrollment in science. This is likely to require considerable investment to create not only the needed curriculum but also the flexible school environment that will permit a different instructional style and arrangement of content.

While the emphasis here is on enhancing science learning, it must be remembered that any policies aiming to achieve productivity gains must be concerned not only with desired increases in learning, but also with the costs associated with such increases. If learning can indeed be enhanced for the majority of students, what will be the costs of implementing the reformed curricula, including changes in in-service teacher education and assessment of student performance? What will be the costs of maintaining effective science curricula in the schools, once development and implementation costs have been met? Also to be considered are the costs of improving teacher preparation, continuing education, and working conditions in schools. Though these issues are beyond the scope of this paper, they need to be addressed when making policy decisions.

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I. INTRODUCTION

The need for increased science learning by of all students has been argued cogently over the last five years (see, for example, National Science Board Commission on Precollege Education in Mathematics, Science and Technology, 1984; National Commission on Excellence, 1983; Science Council of Canada, 1984). This paper addresses possibilities for making improvements in science learning through improving the science curriculum, that is, increasing the efficiency of the curriculum so that more learning takes place without great increases in the costs of science education. Experience has taught that curriculum improvement, to take hold in schools, needs to be supported by improved teacher education, logistics support for hands-on instruction, and effective implementation processes. Nevertheless, it is analytically useful to treat curriculum improvement and each of the enabling contextual factors separately, since they require quite different intervention strategies.

The discussion below focusses on curriculum. The question is: How might the science curriculum in grades K-12 be changed so as to increase the productivity of science education? Before attempting some responses to this question, one needs to define "educational productivity" and "curriculum."

II. DEFINING PRODUCTIVITY

The usual model of educational production features three components: inputs, processes (or transactions), and outcomes (Welch, 1983; Shavelson et al., 1987). In this type of model, inputs include fiscal and other resources, teacher quality, and student background; processes include school quality, curriculum quality (sometimes considered an input), and teaching and instructional quality; and outcomes include student achievement, participation (sometimes considered a process variable), and attitudes and aspirations. (Note that outcomes at one educational endpoint strongly affect one of the inputs--student background--to the next educational phase.)

A somewhat different conception is advanced by the National Research Council report edited by Murnane and Raizen (1987), namely, that what happens in education and what students learn is a function of the behavior of students (including their participation) and the behavior of teachers. These behaviors are mediated by the factors considered as inputs and processes in the more traditional model. The quality of the curriculum is critically important in shaping the behavior of students and of teachers, as is teaching quality, and both curriculum and teaching quality are themselves influenced by other variables generally labeled input or process. This conception has the advantage of doing away with the sometimes artificial distinctions between inputs and processes, both of which need to be considered in any attempt to enhance productivity. Thus, no matter whether curriculum is considered an input or a process variable, it exerts major influence on the behavior of teachers and of students and therefore on the outcomes of education.

There are at least three ways to increase productivity in education:

1. The same amount of learning might be accomplished with a lesser investment of resources. For example, classroom size might be increased but the curriculum and teaching strategies altered so that no loss of learning occurs; lower-paid teacher aides might be used to extend the reach of a more adequately trained and therefore more highly priced teacher; capital investment in computers and related information technology to take over certain teaching tasks might make possible a reduction of investment in human labor (Melmed, 1987); creating a more efficient curriculum might decrease the amount of time it takes to learn

given topics, concepts, and skills. Variations in producing the same learning while lessening the cost include the distribution of achievement and participation: One might wish to increase the science learning and participation of the most able students while decreasing expectations for those students who are not science-inclined, or one might wish to emphasize increased achievement and participation for those very students in order to achieve a modicum of science literacy for all.

2. A more popular conception of productivity gains in education is to have students learn more, preferably at no or little increase in cost. Some possible mechanisms include improved teacher training that leads to better instruction, differentiated staffing that allows master teachers to guide curriculum and instruction, more efficient curricula from which students learn more, and, again, the use of computers for instructional tasks to which they are particularly well suited.

In reality, none of these mechanisms is cost-free, although the costs of several may not be immediately apparent in school budgets. Schools will not directly pay for the costs of improved teacher education, which may in part be borne by teacher training institutions but more likely will be passed on to the individual student, particularly when improvement entails an additional year of study, as suggested by several reform groups (Boyer, 1983; Carnegie Forum on Education and the Economy, 1986; Holmes Group Consortium, 1984). However, individuals having to pay for the increased cost of their education may wish to make up for it through demands for higher pay and upgraded professional opportunities such as sabbaticals, better inservice education, and leave for professional activities (attending meetings, giving presentations, etc.).

Similarly, the costs of improving curricula may initially be incurred by public agencies and foundations through support of relevant research and development, but their likely unconventional format will undoubtedly cause an increase in the cost of textbooks, computer software, and laboratory materials. Even the clearly visible cost of acquiring computers for instruction has additional hidden costs associated with it in the training required to use this and associated technology effectively. In the "more-learning-at-little-additional-cost" conception of increased educational productivity, the same choices as to distribution of increased learning and participation arise as in the previous case: Should increased learning be distributed evenly, emphasized for the science-able, or focussed on students

currently not achieving well? The choice made may well affect what mechanism is to be preferred to achieve productivity gains and, if the mechanism is to be curriculum, how curricula need to be changed to bring about the desired improvement.

3. It is conceivable that the current mood will make possible a considerable increase in the funding for education, provided there is belief and, eventually, evidence that the increase brings about improved learning. The mechanisms are much the same as already noted, although some may be more powerful if greater than marginal improvement is to be achieved. In particular, a restructuring of the classroom environment using information technology and substantially altered curricula and teaching strategies may be necessary to bring about notable increases in learning for large sectors of the student population (Cole and Griffin, 1987).

Because curriculum is the vehicle used to convey what students are to learn, its effectiveness must be considered in any attempt to improve educational outcomes. A primary question is to what extent the curriculum provides leverage for learning increases; a subsidiary question concerns the costs involved in changing the curriculum so as to bring about the desired improvements.

III. DEFINING THE CURRICULUM

The word "curriculum" has acquired many different meanings, both in the professional literature and in lay usage. One set of meanings depends on the philosophy of education being espoused or discerned as the driving force molding curricula. While all education aims to develop the individual, the end purpose of that development is seen to differ according to different interpretations of what happens or should happen in school. One philosophy holds that the purpose is the development of the good citizen and productive worker or, put more negatively, school teaches not only substantive knowledge (the overt curriculum) but also one's own social and economic roles (the covert curriculum). (See, for example, Bowles and Gintis, 1976). The educational outcomes generally considered in analyses ascribing this meaning to curriculum include the level of school achievement (or years of education completed) as well as adult occupational status and earnings. Because these effects are the sum of factors well beyond what happens in school (even though the school itself and its curriculum are influenced by the same factors), such a broad definition of curriculum and its outcomes is not very useful in thinking about productivity increases in education.

A second purpose often stated in philosophical declarations about education is the development of the human potential of each individual; the consequence for curriculum is that it should parallel the natural development of learning in children and adolescents. This poses problems, however, since psychologists have had different models of how children learn, from the behaviorists (Thorndike, 1932; Skinner, 1968, 1953) through Piaget (1954) and his hypothesized stages of development to the current constructionist view of cognitive psychologists in which education is seen as helping individuals improve their own constructions of reality (Resnick, 1987). As better theories of learning are developed, their application may make possible curricula that are more effective than current ones for children of different ages and competencies.

A third more narrowly framed purpose of education is the development of the intellect and intellectual skills through the study of academic disciplines, starting first with the tools of learning and then branching out into the teaching of the sciences, humanities, and arts. This is the purpose which nearly half the teachers and over half the parents (but only a third of secondary-school students)

consider primary and which they (as well as their students) perceive to be the main educational goal of their own school (Goodlad, 1984). In this formulation, the curriculum is the substantive content of education. Most assessments of student achievement and of teacher or school effectiveness also assume intellectual development to be the main purpose of education. Because it is the most commonly accepted goal, and because the elements deemed necessary to its achievement such as effective instructional materials and strategies are the direct responsibility of school, it is also the most appropriate formulation for examining possibilities for achieving productivity gains in education.

Narrowing the definition of curriculum to being the substantive content of education still leaves too wide a domain for the analysis of potential for productivity improvement. Curriculum involves several different elements--the amount of time spent on a topic or a subject, the sequence in which topics or subjects are presented, the specific subject matter content, and the instructional strategies built into the presentation of the subject matter. Although these elements are melded in any working curriculum, they are subject to separate manipulation and therefore need to be considered separately. Moreover, these different elements of the curriculum are expressed in different forms--through the textbook, for example, or the teacher's day-to-day instruction in the classroom--and these forms may deviate considerably from each other.

TIME AS A CURRICULUM ELEMENT

Current policy initiatives have largely focussed on the time element. Can curriculum be defined by the number of courses taken in, say, science, or--in elementary school--the amount of time spent on a specific subject? At the extreme, perhaps so. If no time is spent on science instruction or students chose not to enroll in science courses, then there is no science curriculum.

Much recent policy intervention has sought to bring about improvement in science learning by increasing requirements for the number of science courses necessary for high school graduation (Education Commission of the States, 1985) or entry to state institutions of higher education. A number of questions arise, however. On average, students already were taking 2.2 years of science in grades 9-12 before the new course requirements (usually for two years of science, sometimes for three) were instituted; even in the vocational track, the average was 1.7 years (National Center for Education Statistics, 1984). One may well ask

whether the new mandates materially affect the amount and quality of science to which students are exposed, particularly since there is almost no control over the substantive content of the additional courses mandated. Is exposure to quality science instruction being increased? If exposure is indeed increased, how much more is being learned? If there is increase in learning, how is it distributed? One would assume that the increased requirements will affect mainly students who would not voluntarily have taken that much science before. Will these students be asked to enroll in existing science courses or will special courses be designed to make science more interesting to them? Will such courses be watered down? Or will these students be offered courses in which they enrolled previously, say, in vocational education, but now relabeled science? How many students will avoid the additional requirements by dropping out and perhaps later obtaining a GED?

All these questions need to be addressed before one can document improvement in science learning. (It should be noted that, to document an increase in productivity, one would also need information on the costs of offering more sections of previously existing science courses or designing and offering new courses.) Only the last question can be answered without reference to the content of the courses: one can observe changes in drop-out statistics and try to determine the reasons for any changes. At least two studies, one a new national longitudinal study of secondary school students by the Center for National Statistics (NELS: 88) and one being conducted by the Center for Policy Research in Education (1986) in six states is focussing on this question. The fact that none of the other questions can be answered without examining course content makes it clear that listing number and titles of courses--or time spent on a subject in elementary school--is a wholly inadequate conception of curriculum.

SEQUENCE OF TOPICS AND COURSES

There is an interesting disjuncture in science education in this country: in elementary school, the purpose of science education is commonly construed to be familiarization with "the scientific method" and development of interest in the further study of science; hence, the sequencing of topics is often not considered as critical an issue as the quality of each individual curriculum unit. In secondary school, on the other hand, the sequence of courses has been prescribed for decades, at least for the academic program: first, biology; then, chemistry; and physics last, with earth sciences or general science offered as an

introduction to this sequence. The order of courses is based at least in part on the increasing mathematical knowledge needed as the courses are traditionally taught. At least one physicist (Holton, 1984) has argued, however, that the increasing complexity of the subject matter as one moves from physics to biology ought in fact to dictate the reverse order, with the mathematics curriculum adjusted accordingly. Science offerings and sequences tend to be more hodge-podge for the general and vocational tracks (Guthrie and Leventhal, 1985). So far, there has been little inclination to change traditional course sequences in order to improve science learning.

SUBJECT MATTER CONTENT

Particularly for scientists concerned with the conceptual and factual accuracy of the science being presented to students, course content has been the curriculum component of greatest interest. Reforming the content of the science courses taught in high school was a principal activity of the science education reforms of the 1960s, followed later by attempts to introduce such new subjects as introductory courses dealing with fundamental engineering notions (The Man-Made World) and social-science concepts (Man, A Course Of Study). Development of coherent science curricula for the lower grades followed still later. (For a brief history of the curriculum projects of the 1960s, see Committee on Research in Mathematics, Science, and Technology Education, 1987).

Curriculum change based on reforming subject matter content is enjoying something of a revival today, spurred by the unacceptably low performance of many students in science and by changes in the scientific disciplines brought about by new discoveries, new working methods, and the advent of the computer. Mathematicians and mathematics educators have been particularly active in recommending needed curriculum reform in grades K-12 mathematics (Conference Board of the Mathematical Sciences, 1983; Mathematical Sciences Education Board, 1987). An especially attractive opportunity for curriculum development is presented by the general void in science instruction at the elementary level: the small amount of time devoted to science in grades K-6 has remained virtually unchanged over the last decade (Weiss, 1978, 1987) despite the new emphasis on science in secondary schools. The current NSF/SEE program recognizes the importance of improving this situation; several new projects to develop elementary school science curricula were initiated with NSF funding in 1986.

INSTRUCTIONAL STRATEGY

To some extent, curriculum materials can incorporate particular teaching strategies. A science unit intended to have children learn how to classify objects, for example, may give specific instructions to the teacher on what sorts of objects to use (or even supply the objects), how to present them, and what kinds of commands and cues to give. More fundamentally, sequence and content may be selected and fashioned according to a particular learning theory, as was the case with Science, A Process Approach, developed by AAAS based on Gagne's theories, and with the materials produced by the Science Curriculum Improvement Study which took a Piagetian approach. Interestingly, the willingness to incorporate instructional strategy based on learning theory into curriculum materials is more evident at the elementary school level, possibly because research on learning has concentrated on young children rather than adolescents and adults. Instruction in secondary school is largely based on the college model of lecturing. Several of the reform curricula of the 1960s attempted to introduce teaching through inquiry approaches, but this instructional strategy is not common in today's high school courses. Perhaps the time required for inquiry-based instruction conflicts with the need perceived by teachers to cover the material in the textbook and prepare their students to perform well on tests.

THE INTENDED AND THE IMPLEMENTED CURRICULUM

Different elements of the curriculum are likely to be put together somewhat differently even within the same classroom and for the same subject depending on where one looks for the "curriculum." Is the curriculum what is in the textbook? What a state or local authority mandates? What the teacher actually presents in the classroom? What the student actually studies in and out of school? What the student is expected to know to perform adequately on a given test? All of these? A set of clarifying definitions, used by the International Association for the Evaluation of Educational Achievement (IEA), considers curriculum at three points (see, for example, Crosswhite et al., 1985): the intended or planned curriculum, the implemented or actual curriculum, and the achieved curriculum as discerned in student learning (i.e., educational outcome). The intended curriculum includes such prepared materials as plans, guidelines, and mandates provided by school authorities at the state and local levels; textbooks and--for science--laboratory materials, computer software, and other technology-based aids; lesson plans and auxiliary teaching materials put together by teachers; and tests of

student achievement, particularly if they represent a sampling from the intended curriculum, as is the case with the New York Board of Regents exams.

The implemented curriculum represents the substantive content (including, for science, process skills) as actually presented to the student. For most classrooms, that means the teacher's presentation of subject matter constructed of the various pieces of the intended curriculum--often largely the textbook (Stake and Easley, 1978; Komoski, 1985; Weiss, 1987), but also incorporating district and test requirements--as mediated by the teacher's own instructional strategies. For the implemented curriculum, substantive content melds with teaching quality. As noted, some elements of teaching quality can be built into course materials and other elements of the intended curriculum; others depend on the quality of the teacher.

Efforts to improve productivity through improving the intended curriculum need to deal with the substantive and pedagogic content of its various elements; efforts to improve productivity through improving the implemented curriculum will in addition have to address teacher quality. This is true for traditionally presented materials as well as for content presented through computers, videodiscs, and other learning technologies, since such presentations too are likely to be mediated at least to some extent by the teacher. The interventions needed to improve curriculum content include reformulating course sequences and guidelines for what and how subject matter should be taught at various levels, revising textbooks and related materials to incorporate effective presentations of topics, exploring the potential of computers to increase learning efficiency, creating exercises to assess student achievement that sample from all important learning goals represented in the curriculum, and the like. These interventions are quite different from those needed to improve teacher quality which will need to deal with the preparation and continuing education of teachers and the improvement of their working conditions (Murnane and Raizen, 1987)--subjects beyond the scope of this paper.

To summarize, for purposes of the following discussion, the science curriculum is defined as the intended substantive and pedagogic content of science education to be presented to students in order to develop their intellectual knowledge and skills. The succeeding sections deal with some possibilities for enhancing productivity in science education through changes in the curriculum thus defined.

IV. ALTERNATIVES FOR PRODUCTIVITY ENHANCEMENT

Options for making the science curriculum more effective can be conceived in different ways: One might start with the curriculum elements--time, sequence, substantive content, teaching strategy; one might consider the possibilities for change--for example, adding time or improving the sequencing so as to use the same amount of time more efficiently, changing the substantive content or built-in teaching strategy so that students learn more; or one might examine new opportunities for improving any or several of the elements brought about by the advent of new knowledge (e.g., in learning theory) and new technology (e.g., computers, videodiscs, etc.).

Unfortunately, except for the time element, applicable research is scarce. Suggestions for productivity improvement tend to be based as much on strongly held views about what ought to be (often based on limited evidence) as on a convincing body of research. For example, a major curriculum effort in physics was undertaken in the mid-60s to attract more students to enroll in high-school physics. It was hypothesized that inclusion of historical and cultural material and some astronomy would prove of interest to students not already attracted to physics. Students learned from the course, and a somewhat greater proportion of female students chose to take it, but the overall enrollment was no greater than in straight physics courses. Currently, an interdisciplinary human biology course is being developed as an alternative to the traditional science offerings in grades 7-8 based on the notion that students who are not particularly interested or able in science will learn more from materials that reflect their concerns (see, for example, Moore, 1981; also, recommendations to the National Science Board Commission on Precollege Education in Mathematics, Science and Technology, 1984). The developers propose to have students see themselves as the object of study, viewed through the lenses of anthropology, conventional biology, medicine, sociology, and psychology. Such a course in human biology was originally developed for Stanford University students and evolved into a very popular four-year major. It remains to be seen whether adaptation for a very different student population is possible and will provide a successful replacement for the science currently taught in junior high school. A different example is provided by claims being made as to the teaching efficiency made possible by the computer,

e.g., a 50 percent improvement in student learning, based on experiments involving very limited sorts of instruction involving drill and practice of arithmetic or spelling facts (Melmed, 1987; Office of Technology Assessment, in press).

Without extensive evidence drawn from U.S. schools as to what actual productivity gains might be attainable, this paper will have to limit itself to discussing possibilities that are worthy of exploration based on research, best extant practice, and experience in other countries. Each of the curriculum elements will be considered in turn. While the emphasis will be on enhancing science learning, it must be remembered that any policies aiming to achieve productivity gains must be concerned not only with desired increases in learning but also with the costs associated with such increases.

TIME

There are three ways in which time might be used to make science learning more efficient: more time could be devoted in school to science, as discussed above; the time spent could be used more effectively; and time for out-of-school learning could be increased.

Additional Time

Requiring that more time be spent on science, either by all students (e.g., in elementary school) or by students now deemed deficient in science learning (increasing secondary-school requirements), appears to be a favored solution. However, without evidence on the overall increase in learning or on the additional costs involved in spending more time on science, one cannot draw any firm conclusions on productivity gains. Obviously, students will not learn a subject if they are not exposed to it; research documents the common-sense proposition that the amount of time spent on a subject correlates with student achievement (Wiley and Harnischfeger, 1974; Borg, 1980), particularly in a sequential subject such as mathematics (Jones et al., 1986). Of course, whether students pay attention and are actively involved in the subject matter affects how much they will learn (B. Bloom, 1977; Rosenshine and Berliner, 1978), and this is likely to depend on the quality of the curriculum as well as the teaching. Simply lengthening the amount of exposure without engaging the student may have little effect (Levin, 1984).

More Efficient Use of Time

The caveat on active involvement of students in their learning relates closely to the second way of using time to enhance productivity, namely, to make curriculum materials and instruction more effective. That this is possible is clearly illustrated by the recent IEA assessment of mathematics achievement in grade 8 in 20 countries: The average amount of time spent on mathematics instruction in the U.S.--144 hours per year--compares favorably with most countries that exhibit higher student performance--Japan: 101 hours; Netherlands: 112 hours; Hungary: 96 hours; and on through 13 countries ranking above the U.S. in student performance only two of which spend as much or more time as the U.S. on mathematics instruction (McKnight et al., 1987). Since class size in the U.S. is about at the international average (26 students as compared to Japan's 40), and U.S. teachers appear to be as well if not better trained as their counterparts in other countries, the inescapable conclusion is that at least part of the reason for the disappointing performance of U.S. students lies in the quality of the curriculum.

Curriculum quality entails looking at curriculum sequence, substantive content, and instructional strategy, all of which will be discussed in greater detail below. Curriculum alone, however, cannot accomplish a more efficient use of time. An important ingredient is the commitment of the school and the teacher to the primary purpose of developing students' intellectual knowledge and skills. This is not always present in U.S. schools: Almost 20 percent of the in-class time in elementary school is spent in such non-instructional activities as nonacademic class business and transition between activities (Rosenshine, 1980). Instruction is interrupted with impunity for housekeeping chores and announcements over the public address system (Sizer, 1984). Teachers vary in their ability to keep students engaged in learning, from about 80 percent of time allocated to instruction to 60 percent (Rosenshine, 1980; Goodlad, 1984). Thus, many children spend less than half their time in school on the intended curriculum. Teacher attitude may also be a factor: in Japan, for example, teachers tend to accept responsibility for the low performance of their students, whereas U.S. teachers tend to blame external circumstances, such as lack of student ability (McKnight et al., 1987). These attitudes are mirrored by mothers in both countries (Stevenson et al., 1986), thus reinforcing students' negative motivation.

Learning Time Outside School

The most common way to increase classroom learning time is to assign homework to be done outside of school. This can be an effective strategy for increasing learning, provided the homework is evaluated and discussed by the teacher (Walberg, 1984). However, the amount of time given to science education could be extended considerably more through activities sponsored by institutions other than traditional schools. A good deal of technical education already is provided at the workplace, particularly in industries that rely upon a high rate of innovation (Office of Technology Assessment, in press). Examples in addition to the computer and biotechnology industries are the communications industry and associated unions (e.g., Communication Workers of America) and energy-related businesses such as utility companies. Informal science education programs provided through the print and broadcast media, some aimed at school-age children, also have received attention and some funding from public and private sources (e.g., 3,2,1, CONTACT; the Voyage of the Mimi; Search for Solutions). Successful programs exist at a variety of science museums as well; a few examples are the San Francisco Exploratorium, the Boston Science Museum, the Capitol Children's Museum, the Lawrence Hall of Science, and the Toronto Museum of Science, all of which conduct programs in conjunction with schools and also independent of schools.

There are, however, more innovative possibilities for increasing exposure to science that have hardly been explored. Modern telecommunications technology makes possible networking among a variety of individuals and community organizations. As a consequence, a number of observers foresee the school as merely one node in a learning community that will involve libraries, community centers, local community colleges and other institutions of higher education, museums, workplaces, and the home as well (Cremins, 1976; Fantini and Sinclair, 1985; Goodlad, 1984). Cole and Griffin (1987) describe one such system, the Community Educational Resource and Research Center in San Diego, which links after-school learning centers located in minority communities affected by high dropout rates with the school system and the university. Participants include not only elementary school and high school students but also university undergraduates, graduate students, and university faculty, all of whom expect to learn as well as teach. The activities are managed by coordinating existing resources for minority education from within the university. The lesson to be

drawn is that educational productivity may have to be conceived more broadly than what goes on within the shell of the school building.

TOPIC AND COURSE SEQUENCE

As noted earlier, the problems and the opportunities for improving science learning through changing the instructional arrangement of science topics and courses are quite different at the elementary and secondary levels.

Topic Sequence in Elementary School

Science instruction in elementary school is largely nonexistent. The average amount of time spent on science in grades K-3 is 18 minutes per week compared to 77 minutes per week spent on reading; in grades 4-6, 29 minutes per week is spent on science, less than half the time (69 minutes) spent on reading (Weiss, 1987). Another indication of the lack of importance ascribed to elementary science instruction is the small number of states that, until quite recently, mandated assessment of science learning--three, as of two years ago, 27 currently--as contrasted to mandated testing of reading and mathematics in nearly all states (Council of Chief State School Officers, 1987). Where science instruction exists, it tends to lean heavily on lecture and memorization of text (Stake and Easley, 1978), a teaching method that is condemned by scientists and science educators as inimical to the learning of science in elementary school (Penick, 1983a). Only 9 percent of the nation's elementary school teachers offer hands-on science as a daily experience, whereas 57 percent do in programs that have been recognized as best current practice (Penick, 1983b). But even in the programs that stress hands-on activities, selection of topics often depends on the teacher's familiarity with specific units. There appears to be no content recognized as essential, and the order of the content is deemed close to irrelevant.

This somewhat eclectic approach has been justified on the basis that the important learning in elementary school is the process, method, and nature of science rather than particular scientific subject matter. Moreover, elementary school teachers report that they are not very secure in such subject matter. In the physical sciences, only 16 percent consider themselves very well qualified to teach material relevant at their grade level, and 28 percent do so in the life sciences, as contrasted to 67 percent in mathematics and 82 percent in language

arts and English (Weiss, 1987; see also Helgeson et al., 1977; Stake and Easley, 1978). Given this lack of confidence, teachers may be better off teaching units that excite their students' interest and that they feel competent to handle rather than following a prescribed sequence of substantive topics.

This laissez-faire attitude about science instruction in elementary school is changing. Several of the reports on educational reform published during the early 1980s have urged that science be recognized as a new "basic" (see, for example, the National Commission on Excellence in Education, 1983). While the immediate consequence was an increase in most states in the number of science courses required for high-school graduation, it is now widely recognized that the basis for study of science in secondary school needs to be laid in elementary school. Thus, 34 states have developed frameworks for science at the elementary level; 34 have done so at the secondary level; 14 of the states require that the framework guide the curriculum. These frameworks vary considerably in the amount of detail they contain. Some lay out content to be covered in blocks, e.g., K-3, 3-6, 5-8; some spell out specific topic sequences grade by grade. The science content may be encapsulated in a brief set of instructions as to what students should be able to do (e.g., 13 bullets consisting of such phrases as "Describes mixtures and solutions by special characteristics" and "Identifies models of interdependence of living things") or the kinds of activities they should carry out ("Observes and records the apparent paths of stars," "Conducts a controlled experiment and records and explains the results"); less frequently, a comprehensive framework is produced such as that for California which sets out science goals and objectives for grades K-3, 3-6, and so forth, examples of behaviors that could serve as evidence of the learner's progress, and models that school systems can use to develop their own detailed frameworks. While encouraging local option, the California framework does assert that certain science concepts and skills are basic to scientific literacy, and that the order in which they are introduced and reenforced in later more extensive treatment does matter (California Department of Education, 1984).

As yet, it is too early to tell whether these state attempts are having a marked effect on science learning in elementary school. A major vehicle for doing so is the promised periodic NAEP assessment of science learning, provided the test items are consonant with the states' curriculum goals. It should be noted here that a persistent problem in the assessment of science learning is the limited ability of machine-scorable tests to capture important process skills

emphasized in most goal statements and in exemplary elementary-school curricula. To assess such skills in an adequate manner requires, for young students, expensive observational techniques and training of observers to yield reliable scoring of observed student performance--procedures generally too costly to use on a wide scale. Even for older students who can present answers in written form, evaluation by protocol analysis, though possible (Frederiksen, 1985), is costly when done for large numbers of students. For some purposes, however, nation-wide achievement levels in science rather than state or district achievement levels may be of greatest interest. In that case, the needed sample of students may be small enough and the resources available adequate to allow use of tests containing hands-on exercises such as those adapted from the British Assessment of Performance Units in a recent pilot study by the National Assessment of Educational Progress (1987). Large states or districts could use similar techniques when test results for individual students are not required.

Two sources of curricular sequencing are available that should be examined for their potential for improving current science instruction in elementary school. One is the elementary school science materials supported by NSF in the 1960s, in particular those developed by the Science Curriculum Improvement Study (SCIS) and the AAAS' Science--A Process Approach. Both of these sets of materials represent a coherent curricular approach as well as incorporating many relevant hands-on activities. They also have a record of use and evaluation with students of different backgrounds. Fortunately, these curricula are still commercially obtainable; more important, they as well as the other NSF-supported elementary science materials are now available on videodiscs together with detailed indices as to their content (Rowe, 1987). In the judgment of scientists and science educators who have examined them, these materials still have much to offer (Arons, 1983; Penick, 1983b; Pratt, 1981, Harms and Yager, 1981). Several new efforts along these lines are now going forward, in particular, the development projects supported by NSF in 1986 and the AAAS Project 2061 (Rutherford et al., 1987) intended first to identify what students should have learned in science as they emerge from grade 12 and then identifying the curriculum in grades K-12 needed to get there. It will be some time, however, before information on effectiveness in the classroom will be available on these new efforts.

The second source is the science curriculum that is taught in various countries abroad. In most countries, the core sciences--biology, chemistry,

physics--are taught continuously from upper elementary school on as part of the basic school curriculum. Even when the total teaching time devoted to these subjects is not much different from U.S. classrooms, as for example in West Germany (Klein, 1985), a firm foundation is laid for the more intensive secondary school science curriculum, which continues parallel instruction in all three subjects.

It is particularly interesting to examine the integrated science sequence in countries such as Japan, a where students do considerably better in science achievement than they do in this country. The reason for singling out the Japanese educational system is not only the achievement of the Japanese students, but also that it retains almost all students (94 percent) through high-school and sets very high curricular standards that are virtually met throughout the country's schools (Troost, 1985). One result is that the achievement of Japanese students is less closely tied to parents' education and income than in many other countries, including the United States (Comber and Keeves, 1973; Husen, 1967). Although there are many cultural and organizational factors that are not readily transferrable to this country such as parental attitude (Stevenson et al., 1986) and centralization of educational authority (Troost, 1985), effective curriculum elements may be adaptable.

What is the sequence of science topics and courses in Japanese schools? Troost (1985) describes the curriculum in grades 1-6 in some detail. About a tenth of all class periods is devoted to science, starting with grade 1. The instruction emphasizes observation and experimentation involving active manipulation of objects. Virtually every primary school has a science laboratory, and most schools have at least two. Textbooks are coordinated with the inquiry-oriented curriculum and are handsomely illustrated. The topics taught are grouped into three areas: Living things (plants, animals, human body), matter and energy (aqueous solution, substance, air, forces, heat, magnets, electricity, light, sound), and the earth and universe (weather, rocks and soil, celestial bodies). These topics do not all receive equal emphasis; several are taken up throughout the grades (plants, aqueous solution, weather) whereas others are treated only once (human body, air, magnets, sound, celestial bodies), a good example of what McKnight et al. (1987) have called the pattern of intensity of a curriculum. The topics are pursued in greater detail and with increasing academic rigor and abstraction in grades 7-9, on the assumption that the elementary curriculum has

provided a substantive experiential base. By upper secondary school, courses parallel the disciplines (physics, chemistry, biology, earth science). Most students at that level, which permits some choice, take at least one course per year; 25 percent take two science courses per year. The topic sequence exemplifies the spiral curriculum advocated by science educators as optimal for science learning (Moore, 1981). Such an organization allows exploration of core scientific concepts in depth, provided that needless and unproductive repetition is minimized. The spiral curriculum also offers reenforcement for learning science process skills, as students progress to increasingly complex laboratory investigations, field work, and independent inquiry and research. There are dangers, however: failure to build depth and progression into a spiral curriculum and the tendency to treat all topics with equal weight can lead to the kind of low-intensity curriculum that characterizes U.S. elementary-school mathematics (McKnight et al., 1987).

Recent Canadian recommendations by the Science Council of Canada (1984: 48) follow a similar approach. The Council recommends that "[e]lementary science programs should be focussed on the student's environment and include materials from such fields as geology, agriculture, forestry, botany, anatomy, engineering, health science and nutrition. Middle-years science programs should gradually add descriptive aspects of physics and chemistry. Advanced theoretical concepts should be postponed until higher-level courses or university....Ministries [of education] should incorporate a science-technology-society emphasis in science courses at all levels...50 per cent in courses at the early-years level, 33 per cent at the middle-years level, and 25 per cent at the senior-years level."

Course Sequence in Secondary School

The usual course sequence in grades 10-12 for the academic or college-bound track in U.S. schools is biology, chemistry, and then physics, although the chemistry/physics sequence may be reversed for some students in small schools that offer these two courses in alternate years only. The sequence in upper secondary school is preceded in grades 7-9 by general science or earth science. Able students start the sequence earlier, which allows them to take an advanced course in grade 12. Each course is a "stand-alone" semester or, more commonly, two semesters; there is no sequential building of knowledge and skills through a series of years. The nearly unbreakable dominance of this sequence was demonstrated by the failure to find widespread acceptance of an alternative to the

physics course introducing engineering principles and topics on the interaction of society and technology (The Man-Made World), despite the high quality of the text and accompanying materials and the ostensible relevance of such a course. (The course has since been successfully adapted for lower-division college students and is being widely and successfully taught. At this time, as scientific and technological literacy for all students has become a primary educational concern, this sort of approach is being urged once again for high school students. See, for example, Peel, 1981). The inflexibility may be occasioned as much by the requirements for college entrance set by institutions of higher education as by the reluctance of schools to make any changes.

Science offerings for students in the general or vocational tracks appear to offer somewhat greater variety but no particular vision of a core of science knowledge that all students ought to master. The biology course commonly taken in 10th grade might be followed by a course in physiology or in environmental science, in wildlife zoology, animal behavior, landscape gardening, applied physics or applied chemistry, or in astronomy or earth science (Guthrie and Leventhal, 1985).

The stand-alone nature of the courses in all three tracks permits them to be offered without any preceding science preparation or any need to assume further science study. This fits both the lack of science instruction in the lower grades and the proclivity of most U.S. high-school students to drop science as soon as possible. Would any other sequence of courses in secondary school be more effective without an accompanying reform in elementary school that lays a sound formation for further science study? Placing physics as it is currently taught in 12th grade (or 11th grade for advanced students) makes sense, given that some knowledge of mathematics is needed. On the other hand, physics deals with less complex systems than does chemistry; chemistry is a prerequisite for the study of the fundamental processes within living organisms; and all three of these sciences contribute to the earth sciences. Thus, there would be intellectual logic in turning the usual sequence upside down. Another argument for the status quo, however, is that students are more interested in and need a knowledge of living things. The fact that nearly two-thirds of students take biology, whereas only a third take chemistry and somewhere between 10 and 15 percent take physics, makes this argument plausible. Yet, these enrollment statistics may well be an artifact of the existing sequence--students will drop science as soon as their

science requirements are met, no matter what the courses--or the perception that physics is more difficult than chemistry and chemistry more difficult than biology.

Courses in middle and junior high schools are particularly problematical. Hurd et al. (1981) report that there are two major patterns: a three-year sequence of life, physical, and earth sciences, or a one-, two-, or three-year offering called general science. No matter which sequence is followed, programs at this level tend to be watered-down versions of their high-school counterparts, with great emphasis on the learning of science facts. In most programs, students have little opportunity to experiment on their own.

There is scarce evidence from the U.S. experience to indicate that merely changing the established course sequence for the academic track or creating a new one for the general and vocational tracks would bring about any great change in science learning of students who currently enroll in science courses or would encourage more students to enroll. What is needed is a coherent plan for introducing key topics through hands-on experiences in the early grades and then returning to coherent sequences of them in increasingly rigorous fashion as students progress through school until they acquire the necessary quantitative and reasoning skills to profit from instruction in the individual scientific disciplines. Even then, instruction in parallel throughout the grades in the life and physical sciences, as practiced in most other countries, may be preferable to the layer-cake approach that characterizes U.S. high schools. Assessments of the scientific literacy of the adult population in this country (Miller, 1983, 1986) document the minimal retention of science learned in school as presently organized.

CURRICULUM CONTENT

In a sense, decisions on time, sequence, and instructional strategy depend critically on content, i.e., on what the student is expected to learn. Unfortunately, especially at the elementary school level, it has been easier to achieve some consensus on the processes and methods that students should understand as being associated with science than on the core of conceptual and factual knowledge they need to learn.

Goals

The inability to deal in an intellectually rigorous fashion with curriculum content is not confined to science education or to lower education (Sizer, 1984; Cheney, 1987; Ravitch and Finn, 1987; A. Bloom, 1987; Hirsch, 1987; Boyer, 1986). Much of the vagueness and vacuity come about because of the attempt to accommodate the very real differences in philosophy and purpose that animate the country's educational system. On the face of it, schools subscribe to all educational purposes in equal degree, making for remarkable unanimity across the country (Sizer, 1984), yet this unanimity breaks down when it comes to the choice of specific subject matter.

In science, as in other subjects, debates on curriculum content mirror the philosophical differences: Should the teaching of fundamental processes and concepts of, say, biology take precedence over an understanding of one's own body, good health practices, and preparation for sexually responsible conduct leading to good parent behavior (i.e., intellectual development through study of the discipline versus development of the good citizen able to handle individual and family responsibilities)? Should the connections between science and technology be emphasized, including discussion of the ethical dilemmas raised for society by the rapid development of, for example, biotechnology (i.e., understanding of the effects of science and technology on society and development of social responsibility)? What is the appropriate balance between learning the powerful abstractions of the basic scientific disciplines and their most important applications that continue to change society? What is the place of technology education in the curriculum? Rather than academic learning, should the main objective be for students to acquire the technical skills and ability for continued learning needed to contribute effectively to the U.S. economy (i.e., development of productive workers competitive in the world market)? Should there be different goals--and therefore different curricula--for students of different competencies and backgrounds? Which is of higher priority: the development of scientific talent and technical manpower or achieving a modicum of scientific literacy for all students?

These goal conflicts cannot simply be papered over, particularly when student learning is to be increased through curriculum changes. Curriculum efficiency can be assessed only if the learning goals are clearly laid out. An example of the confusion that arises through shifting goals is provided by the

judgments made about one of the 1960s curricula, the physics course developed by the Physical Sciences Study Committee (PSSC). The developers clearly stated that they wanted to create a sounder course for students who elect to take physics in 11th or 12th grade, i.e., the 10-15 percent traditionally enrolled, yet the course was criticized for not attracting greater numbers of students to the study of physics--never one of its goals.

Influences on Curriculum Content

How are the differences in goals handled? Ultimately, local school districts have responsibility for the curriculum taught in the schools. Often, this responsibility is carried out through textbook selection, with the textbook serving as the foundation of the curriculum. Since the early 1980s, however, states have become more active in providing districts with guidelines on science instruction. In some states, such guidelines are mandatory, in others, voluntary. States that mandate science content (e.g., New York) or offer assistance to local districts in meeting instructional goals (e.g., Connecticut, Michigan, Pennsylvania) tend to generate greater commonality in curriculum content than those that limit their requirements to number of credit hours needed for graduation.

A less obvious influence making for commonality of content among the science curricula of different school districts arises from the use of nationally developed and standardized tests. This influence will grow as states increasingly mandate assessment of science learning. Pressure to have students obtain adequate or high scores is likely to lead teachers to emphasize the material on the tests; in turn, the tests, to encourage wide usage, will tend to emphasize what is most likely to be taught in most schools. A greater conformity in curriculum is the inevitable result. This conformity is already evident for the secondary-school academic track, particularly for advanced placement courses which require standard examinations before college credit is given.

The main centralizing force, however, is the textbook. Reliance on the textbook in all instruction is great; surveys have found that well over 90 percent of the curriculum content being taught in both elementary and secondary school is contained in the instructional materials being used, with the textbook occupying students and teachers about 70 percent of the time (Komoski, 1985). A recent survey specifically of science and mathematics education documents similar findings: in secondary school, 93 percent of the teachers use textbooks for

teaching science; 89 percent do so in grades 4-6 (Weiss, 1987). A similar survey done some years ago showed that one half of all science classes used a single published textbook or program, and many of these used one of four or five of the most popular texts (Weiss, 1978). These texts, in an attempt to ensure an adequate market, generally pay close attention to the requirements set by state textbook adoption boards in some of the more populous states, such as California, Florida, and Texas (Apple, 1985). Critics have argued that the need for public acceptance leads to trivialization of content in science textbooks, providing a superficial treatment of a wide variety of topics without depth or rigor (Hurd, 1982; Taylor, 1984; Komoski, 1985).

Professional scientific societies have been active in developing guidelines on what should be taught in high school courses in their disciplines (e.g., American Chemical Society, 1984; Joint Committee on Geographic Education, 1984; Conference Board of the Mathematical Sciences, 1983). While it has not proved easy to come to agreement on the core knowledge to be learned within the stand-alone, single-discipline courses of the senior high school, the difficulties are multiplied when more than one discipline is involved. Thus, the attempt to develop a rigorous physical sciences course was given up by the Physical Sciences Study Committee in favor of concentrating on physics. It is not surprising, therefore, that no consensus has been reached among the scientific disciplines on the core concepts and factual scientific knowledge to be included in the elementary school curriculum. The AAAS plans eventually to develop the needed synthesis in Project 2061 (Rutherford et al., 1987), working down through the grades from a coherent statement of what the scientifically literate high-school graduate should be expected to know.

The present lack of consensus among scientists themselves as to what content really matters is no doubt part of the reason why the emphasis in elementary school tends to be on learning such general processes as observing, comparing, ordering, measuring, classifying, and the like. Perhaps one should say learning <u>about</u> these processes, for, as noted, all too often not only substantive content but also "the scientific method" are taught from the textbook rather than through hands-on activities that model scientific inquiry. On average, well over half the instructional time given to science is spent on lectures and reading about science, less than a fifth on working with hands-on or laboratory materials (Weiss, 1987). It should not come as a great shock that liking for science drops

from four-fifths of students in upper elementary school to two-thirds in secondary school compared to a much smaller drop for such subjects as arts and physical education that actively involve the student (Goodlad, 1984). (Attitude measures are quite unreliable [Munby, 1983], but the direction is always the same. Some studies have found that only a fifth of secondary school students--rather than two-thirds--have a positive attitude toward science and that the popularity of mathematics drops from 48 percent in grade 3 to 18 percent in grade 12 [National Assessment of Educational Progress, 1979; Hurd et al., 1981]). Participation in science continues to diminish through the secondary grades, as course enrollment becomes voluntary (Raizen and Jones, 1985). Clearly, most students are turned off by the current science curriculum.

Productivity Improvements

What can be done to make the science curriculum more efficient? Three possibilities emerge from the preceding analysis: 1. Introduce coherent substantive curriculum content into elementary school to provide a sound foundation for secondary-school science; 2. provide sufficient challenge and opportunities for student involvement in science learning at the lower levels to maintain interest (and increase student enrollment) at the secondary level; and 3. reform the secondary school curriculum so that courses, no matter whether aimed at the science-able or designed for general scientific literacy, deal with a limited number of core topics in depth rather than presenting a smattering of many topics as at present.

If these suggestions were to be implemented successfully, two productivity improvements could be expected to result: 1. At equivalent stages of their mandated education (e.g., end of elementary school), students would know more science than they do now, and 2. students would further increase their science knowledge and achievement by opting to enroll in additional science courses beyond those required. The three suggestions are consistent with the recommendations of the Committee on Indicators of Precollege Science and Mathematics Education (Murnane and Raizen, 1987) that frameworks be constructed for the following curriculum blocks: grades K-5 science, grades 6-8 science, grades 9-12 literacy in science, and grades 9-12 science for college-bound students, and that curricula be evaluated for depth of treatment as well as breadth of coverage. The frameworks would serve to inform state and local

agencies as to desirable content of textbooks, tests, and their own curriculum guidelines. In view of the already existing tendencies making for a common curriculum, the specter of a "national" curriculum possibly raised by such a recommendation is not nearly as threatening as the present condition of the curriculum which leads most students to learn much less than they are able.

Specification of curriculum content that meets the three reform suggestions made above should build on current efforts by the AAAS, the professional societies, and the states. But the reforms will not come about without strong leadership from the scientific community. Scientists need to define the core concepts and knowledge that make up their disciplines, but they need to do so in cooperation with individuals --teachers, educators, cognitive scientists, learning researchers--who understand the reach of a student's intellectual development at any given level. Curriculum content and science learning achieved in other countries can provide a model for what is possible, if not necessarily desirable for whole-sale adoption in this country.

Scientists also need to participate in the definition of goals for science education, but this is too important to be left to scientists alone. The "recipients" of the learner must help set goals and expectations as well, that is, the teachers at the next stage of education and, ultimately, the employers. At present, expectations are rather low. The attitude tends to be: "Just provide the general learning tools at your (the preceding) level, and I'll teach the real physics (chemistry, calculus, computer programming, technical knowledge, job skills, or whatever)" (See, for instance, Panel on Secondary Education for the Changing Workplace, 1984.) If neither teachers nor employers expect any substantive learning in their fields at preceding levels of education, is it surprising that there is so little?

The only evidence that the science curriculum can be made more efficient is provided by the experience of other countries (see IEA test results for U.S. student performance in science compared to that of students in other industrialized nations) and by a select number of high schools that, year after year, have produced high achievers in science (see, for example, the annual list of Westinghouse Science Fair Winners and their schools). Neither of these provides convincing evidence for what can be done for the great majority of students in this country. Experimentation must take place to establish whether the suggested reforms actually increase student learning and enrollment in science. This will

require considerable investment to create not only the needed curriculum but also the flexible school environment that will permit a different instructional style and arrangement of content. It will also require agreement on curriculum goals and assessments that plumb all these goals. If learning can indeed be enhanced for the majority of students, what will be the costs of implementing the reformed curricula, including changes in in-service teacher education and in assessment of student performance? What will be the costs of maintaining effective science curricula in the schools, once development and implementation costs have been met? These may be even more difficult questions to answer than the one on increased learning achievement, since--judging from the experience of the 1960s--the reformed curricula are likely to require teachers educated in greater depth both in subject matter and in appropriate teaching strategies, reformulation of classroom and school organization, continuing instructional support services now absent from most schools, and cyclical revision of curricula as the substance of science and of science teaching changes over time.

INSTRUCTIONAL STRATEGIES

The experience of science educators, the research of cognitive scientists, and the possibilities opened by the advent of inexpensive microprocessors and associated technologies all provide possibilities for improving the ways in which science is currently taught. Unfortunately, exploiting these possibilities will require substantial change in the way most science classes are now conducted.

Learning Science Through Hands-on Experience

Researchers in science education have analyzed the results of the reform curricula of the 1960s, which stressed discovery-based learning through hands-on experiences and laboratory exercises, and documented their greater efficacy for learning higher-order skills (reasoning, problem solving, dealing with unfamiliar situations) than traditional materials without any loss in factual learning (Shymanski et al., 1983). The National Science Teachers Association in its Focus on Excellence series (Penick et al., 1983-1984) has published several monographs that feature outstanding science instruction in elementary school and in each of the disciplines in secondary school; almost all the featured programs have a strong hands-on or laboratory component. The National Research Council's Committee on Indicators of Precollege Mathematics and Science Education

(Murnane and Raizen, 1987) has identified the dimensions of scientific literacy to include an understanding of the scientific world view, the nature of the scientific enterprise, scientific habits of mind, and the role of science in human affairs. It is difficult to reconcile the goal of teaching science as a way of viewing the world or scientific habits of mind with instruction that consists of reading texts or hearing the teacher lecture about the scientific method or about experimental procedures. Yet, these are the predominant teaching modes in classrooms at all levels of education (Weiss, 1987; Goodlad, 1984; Stake and Easley, 1978). No wonder, then, that according to the National Assessment of Educational Progress, students have improved their test scores on items that involve rote learning and are losing ground in applying their learning to problems that involve a modicum of reasoning and creativity.

Contributions of Cognitive Science

Collaborative studies between researchers investigating learning and experts in one of the sciences taught in school (largely physicists or mathematicians) are providing interesting information that may help improve instruction in the long term. Resnick (1987, 1983) has summarized some of the cogent findings: Learners construct understanding; they do not merely passively reflect what they read or are told. Hence, they come to science classes with preformulated notions that may conflict with the scientific concepts being taught which remain unconnected to their past experience and hence less powerful than their own "naive" theories. One implication is that science teaching needs to start as early as possible, with as many science experiences provided to young children as the teaching day allows. In this respect, the findings of science educators and cognitive scientists reinforce each other.

Another finding coming from cognitive research is that higher-order thinking is driven and supported by specific subject-matter knowledge. Research on how experts in different fields solve problems as contrasted to novices indicates that their greater competence comes from greater knowledge of specific facts and organizing principles, as well as their greater experience. This implies that instruction in thinking skills needs to be embedded in a coherent presentation of the substantive subject matter of a discipline, calling into question the laissez-faire approach to science instruction in elementary school.

Resnick (1987) points out that effective instruction deals not only with

learning but also with motivation to learn. Here, again, interesting hands-on science experiences in the early grades teach not only the processes and some of the substance of science but also critical communication skills, as demonstrated with Science--A Process Approach, an elementary-school curriculum developed by AAAS. Parental and teacher attitudes are all important in motivating students, as demonstrated by the previously cited example of Japan, but not easily influenced by policy. Another powerful motivator is the computer terminal, as discussed in the next section.

The Promise of Technology

Of all the alternatives for increasing the productivity of science education, investment in computers and associated information technology and in accompanying innovative and creative software offers the least exploited potential. Other information-based systems, such as banking, insurance, and communications, have materially altered what they do and how they do it through integrating the computer into their operations, thereby greatly increasing their productivity. Education alone, the largest knowledge-based industry of all, stands virtually unchanged. The next decade will tell whether the potential offered by the new technologies will be realized for the benefit of the students in the country's schools.

A recent report by the Office of Technology Assessment (in press) estimates, perhaps somewhat optimistically, that significant use of computers and communication hardware in education could bring about a 50 percent increase in productivity in elementary and secondary schools at expenditures no greater than current schooling costs. Because students would spend 25-50 percent of their time at terminals (costing $250-500 per student as an initial investment), student/faculty ratios could be increased to 40 or 50. Much of the traditional lecture time would be given over to small-group tutorials as well as time spent on terminals, either individually or in groups. Teachers would be relieved of their many non-professional chores and command considerably higher salaries, e.g., increases of 40-50 percent, both of which conditions could be expected to attract highly competent individuals to teaching.

How would such a system produce the predicted learning gains? The new technology makes possible the following educational improvements (Lesgold and Reif, 1983; Office of Technology Assessment, in press):

1. Instruction can be tailored to the individual needs and learning style of the student. Current classroom practice aims at the "average;" there is no way in which a teacher can tailor instruction to each of 30 students (Gallagher, 1983). Computer programs, however, perhaps created by gifted teachers themselves, can take into account the knowledge that individual students have and the pace and learning method that best suits them, as diagnosed by the computer itself. Since the computer can record a student's progress as he or she proceeds, both the student and teacher receive immediate feedback on the effectiveness of the chosen learning strategy and can change or augment it. Prototypes of such intelligent tutoring systems have been created for teaching geometric proofs and programming (Anderson et al., 1985).

2. Computers can be used to create new learning environments. Experiments too dangerous or lengthy for the classroom can be simulated; situations impossible to observe in reality can be modeled through speeding up or slowing down time or through creating imaginary worlds such as a frictionless universe to illustrate Newton's laws of motion (diSessa, 1982); graphic animation can illustrate phenomena impossible to demonstrate in the classroom. This capability allows students to explore ideas and hands-on learning in ways never before possible.

3. Computers can represent knowledge in many different ways. For example, data may be displayed in form of a physical phenomenon, a table, a graphic representation, or an algebraic function, permitting students to work with the representation most meaningful to them. Moreover, the representations can be linked, so that students learn to understand their relationships and which representation is most usefully employed to analyze a particular problem.

4. Computers can provide powerful intellectual tools for both students and teachers. They can calculate and manipulate equations; they can retrieve information from large data bases. Problem exercises in science can be based on real data rather than being artificially constructed based on time limits for gathering data and doing long-hand arithmetic.

5. Computers in association with telecommunications technology can create learner networks apart from the physical location of the learner. Rather than isolating learners and teachers, computers provide a wide range of choices of how learning can occur--through individual study, through lectures or peer interaction, through collaboration among individuals of different competencies (Cole and Griffin). Specialized instruction can be brought to any school, no matter how small or remote; out-of-school learning sites can be connected to schools, institutions of higher education, or experts in industry; teachers can have access to each other's best ideas as well as those of scientists and science educators.

6. Computers can motivate learning. The computer is an ever-patient tutor. The student can control the pace of instruction, can repeat sequences not fully understood or change the approach, can skip material already familiar, or can take excursions into material of special interest. The open learning environment that the computer makes possible could demonstrate to nearly all students the joy of learning and the power of knowledge.

While these educational features made possible by the computer would improve all learning, and all of them are important in science education, the features discussed in points 2. and 3. are of special value in enhancing the learning of science. Unfortunately, the real potential of the computer is unlikely to be realized in the near term. Computers in schools are becoming widely accessible, but they are mainly used as adjuncts to traditional classroom organization and instruction (Becker, 1986), repeating the history of such earlier educational technology as programmed instruction, educational TV, and slides and filmstrips. By 1984, almost 95 percent of all senior high schools were using computers, largely to teach programming. In elementary school, 67 percent of teachers recently surveyed reported having computers available for teaching science; the main instructional use was for drill and practice (Weiss, 1987).

There are several reasons for the failure so far of the new technology to make serious inroads: Schools have invested in (or been given) microprocessors with inadequate power for the applications suggested above; the necessary

software exists only in form of a few prototypes; demonstrations of the educational power of computers and telecommunications technology have largely come from the military, private ıdustry, and higher education--that is, from outside the K-12 education system; and computers in the classroom are seen as a threat by many teachers and parents who fear that technology will dehumanize education. Behind this fear lies the deeper threat of a radical reorganization of school.

This paper argues, as do others (Goodlad, 1984; Sizer, 1984), that such a reorganization is necessary if effective education is to become the norm for almost all students. It further argues that technology, far from dehumanizing education, makes possible a rich educational environment that will allow teachers to concentrate on their teaching and enable students to learn more. But several critical steps are necessary first: schools must be encouraged to acquire appropriate hardware (specially designed for educational rather than business purposes, if necessary); software must be developed; and demonstrations of what is possible must be set up. Each of these steps will be costly, particularly the development of software. In the absence of a strong market, it is unlikely that private industry will make the necessary investments; several past attempts have proved discouraging and occasioned the private sector to withdraw from innovation in education (Rhodes, 1987). Nor can individual states or school systems, no matter how wealthy, carry on the sustained development activities that will be necessary. Until there is a decision at the national level that education is as important as other sectors of the economy and warrants the necessary research and development to improve its productivity through the application of computer and telecommunication technology, the potential will continue to remain just that.

SUMMARY AND DISCUSSION

There are several possibilities for improving the effectiveness of science education through changing the curriculum:

- Time in the classroom needs to be used more efficiently through the use of improved curricula;

- The time spent on science education could be expanded through melding out-of-school science activities with formal classroom instruction and homework, using modern telecommunications technology;

- The science curriculum in elementary school should consist of a coherent sequence of core topics that initially build on the students' experience and environment and advance to increasingly descriptive knowledge and abstract concepts as students mature;

- Instead of the current stand-alone science courses offered in secondary school, there should be a parallel progression of courses in the life and physical sciences building on the previous years' learning at least through grade 11, as is the case in the school systems of most other countries.

- To provide guidance on the substantive content of the science curriculum, scientists together with teachers from the relevant grade levels, science educators, employers, and others with interest and understanding of current needs in science education must define its goals and the core knowledge and understanding to be expected of all students;

- Depth of treatment of the core material needs to be built into the curriculum from elementary school on, even at the expense of having to omit favorite topics;

- Hands-on experiences in elementary school and laboratory investigations in secondary school are an indispensable part of science instruction, fostering both student understanding and student motivation;
- Science instruction, to become more effective, should take advantage of

leads being provided by current research on science learning, science teaching, and teacher education;

- Improvements made in curriculum and instruction must be reflected in the ways that student knowledge and performance in science are assessed, and assessments must plumb all important curricular goals;

- Computers and associated telecommunication technology offer great potential for restructuring science education so as to enable all students to become scientifically literate, but this opportunity--because it entails the greatest change--is the least likely to be exploited.

An important caveat needs to be attached to all these possibilities. Although each deserves separate exploration, development, and piloting, including adequate investment of professional time and financial resources, none can be expected to work in isolation. A rethinking of all aspects of the science curriculum is necessary--time, sequencing, content, and instructional strategy. Even that will prove a futile effort unless the problems of the schools are thought about in a systemic way: What kinds of teachers are needed to teach the reformed curricula? How must schools and classrooms be organized to permit effective teaching of the reformed curricula? What connections must be built between schools and other institutions, including the communities in which the schools are located, to enhance and reinforce student learning?

The Committee on Research in Mathematics, Science, and Technology Education (1985, p.44) stated the problem as follows: "...the past decades have seen a cumulation of knowledge from several pertinent disciplines and the development of new technologies, but application to mathematics and science education, as to all education, has been episodic, unsystematic, and limited in scope....At present, there is no mechanism to serve the function of integrating the new knowledge and technology ... and applying them to the development of improved systems for teaching and learning science....In other enterprises, this integrative function is called systems design and engineering....Modern educational activities, too, should be considered a system in which improvement of components in isolation may not lead to improvement of the overall system."

Although the application of engineering principles to social systems is

fraught with problems, there is an important lesson in the analogy. Curriculum reform, no matter how soundly based, will not by itself enhance educational productivity unless it is accompanied by concomitant changes in teaching and in classroom and school organization. This much the last quarter century of educational reform should have taught all who want to improve education. The country will continue to experience disappointment and failure in creating effective education unless this lesson is taken to heart.

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